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This report summarizes the work conducted under the grant. The goals of this research were to develop performance models of multi-hop broadcast networks and then utilize these models to suggest optimal routing and control parameters. The authors decided to concentrate their initial effort on the Slotted Alone access protocol and then generalize to other protocols later. More details can be found in the papers referenced in this report.

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FINAL REPORT

"Advanced Communication System Studies"

May 15, 1980 to May 14, 1982

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## A. TECHNICAL SUMMARIES

The following are brief summaries of the results obtained in the four technical areas of interest. Details are available in the references given at the end of the report.

## 1. EFFICIENT PROTOCOLS FOR BROADCAST NETWORKS (Dr. Silvester)

### Introduction

In this report, we give a brief summary of the work conducted under this grant. More details can be found in the referenced papers [1-10].

The goals of this research effort were to develop performance models of multi-hop broadcast networks and then utilize these models to suggest optimal routing and control parameters. We decided to concentrate our initial effort on the Slotted Aloha access protocol and then generalize to other protocols later.

### Capacity and Maximum Throughput

In the first year of this grant, we concentrated on determining the capacity or maximum achievable throughput that can be obtained in a multi-hop broadcast network.

In [1], we developed a general network model and obtained a general approach for solving for the capacity and maximum throughput of broadcast nets.

We use the words "maximum throughput" to mean the maximum end-to-end traffic that can be carried by the network without overloading any of the links, such that the traffic pattern is satisfied, for a specific access protocol. In [6,10], we present a model for determining the maximum throughput of the Slotted Aloha protocol. This results in a non-linear optimization problem, where optimization is performed over the set of transmission probabilities (channel access rights). We have used this procedure to find the maximum throughput for many simple networks, but are still encountering some convergence problems for complex nets.

Capacity, on the other hand, is defined to be the maximum throughput that can be achieved for any access protocol. This, thus, corresponds to perfect scheduling or Time Division Multiple Access (TDMA). While TDMA may not be feasible in an operational network, it is still useful to know the network capacity since this allows us to make comparative studies of other more useable protocols. We show that the perfect scheduling problem can be solved by a generalized coloring algorithm, which allows multiple colors to be assigned to nodes [4]. We give an algorithm, which is found to be efficient for the kind of networks encountered in practical applications. We also introduce the concept of fractional coloring, which corresponds to splitting the time or frequency slots into subslots, and show that this can increase performance in some networks.

Network capacity can also be improved by changing the network topology (changing transmitter power levels, etc.). In [5], which was initiated while this author was a Ph.D. student, we study the effect of topology on capacity for networks that have a regular structure.

Throughput/Delay

Perhaps the more valuable part of our studies is concerned with obtaining results on delays in broadcast networks. The main difficulty here is the dependency between the service time (time to successfully transmit a packet) from one node and the queue sizes at the other nodes in the network. This is a common problem of all efficient multiple-access protocols currently in use. Our approach to overcoming this problem is to assume independence between the nodes, model the interactions in a probabilistic manner and then use an iterative technique to refine the model of interaction [8].

This approach was first applied to fully-connected Slotted Aloha Networks in [3]. Excellent agreement was found between the model's results and those obtained by numerical solution of the underlying Markov chain (an exact solution, only feasible for very simple nets). We then proceeded to generalize these results to the multi-hop environment, [9]. For these larger more complex networks, it was not possible to obtain exact solutions, and so we compared our model's results to simulation, again finding excellent agreement.

We also applied this approach to other access protocols: CSMA [7], CSMA-CD [10]. In all cases (where simulation results were available) good agreement was found. It appears that this approach is extremely useful in obtaining throughput/delay performance results for a wide variety of multiple-access protocols including others that we have not as yet studied.

Spread Spectrum

We were also interested in modelling the performance of networks utilizing spread spectrum as a signalling technique. In particular, the effect of the access protocol on performance and the way that the access protocol interacts with the specific spread spectrum technique, (Direct Sequence, Frequency Hopping, or Time Hopping) being used, is of interest. In [2], we studied a particular Spread Spectrum Access Protocol combination and studied the scheduling conflicts that arose.

Summary

The results obtained during the course of this grant have applicability to a wide variety of broadcast network applications and with additional work can be used to study network control issues such as routing and flow control. As a result of this study, we now have the ability to: i) Determine the capacity of an arbitrary multi-hop broadcast network; ii) Obtain (good) approximate delay/throughput performance for a variety of access protocols in both fully-connected and multi-hop networks. In addition, we have started to identify the tradeoffs that exist in selecting an access protocol fo use in a Spread Spectrum network.

## 2. TIME AND FREQUENCY TRANSFER METHODS (Dr. Lindsey)

### Background

In recent years, people have shown great interest in very accurate world-wide time and frequency distribution networks (LORAN C, GPS, etc.). Existing networks are almost exclusively plesiochronous which implies the need for extremely accurate clocks at each node. There have been several suggestions in the literature to use delay-compensated-mutually synchronized clocks. All these theories are, however, only applicable to stationary networks while the most interesting applications are not stationary, e.g., the Global Positioning System (GPS). According to preliminary results, mutual synchronization seems to be a very promising concept for future network architecture.

One major problem associated with the mutual synchronization approach has to do with time-frequency instabilities produced by path delay and path delay variations between nodes. For the case where the nodes are stationary, ad hoc techniques have been proposed and analyzed as delay compensation methods. However, for the case of non-stationary network nodes, there appears to be no known mutual synchronization technique, ad hoc or otherwise, which successfully transfers time and frequency between network nodes. There are numerous applications where this problem arises, viz., accurate position location systems, synchronous communications, command and control networks, clocking systems in high-speed digital computers, etc.

### Progress

The research on time and frequency transfer networks has been concentrated in four areas:

1. Development of Mathematical Models: A unified mathematical model encompassing plesiochronous master-slave and mutual synchronization systems was developed. This unified mathematical model enables a fair comparison of the different time and frequency transfer networks.

2. Stationary or Near-Stationary Networks: Several mutually-synchronized time and frequency transfer networks have been analyzed based upon the above mentioned mathematical model. The analyzed networks are the basic

mutual synchronization without a delay compensation, delay line compensated networks [16], the equational timing system, the returnable timing system, and advanced clock networks [11,20].

The analysis included the evaluation of the steady state network frequency, steady state time differences between clocks, the decay rate of transients (stability) in the networks and their dependence on network parameters, e.g., channel delays, loop gains, and network topology.

Also evaluated were the influence of clock drift on the network frequency and the time errors between clocks [15,19,20].

3. Nonstationary Networks: Several techniques to synchronize geographically separated clocks in the presence of varying channel delays have been analyzed in two theses [19,20].

4. Phase Noise Performance: The influence of clock phase noise on the frequency stability and time interval stability has been investigated based upon the theory of structure functions [19]. The performance of various synchronization systems has been compared in [21].

## Master-Slave vs. Mutual Synchronization

Master-Slave versus the mutual synchronization techniques have been investigated [15] quantitatively. The subjects of this comparative study include delay compensation requirements, steady state frequency, steady state phase differences between clocks, probability distribution of the phase differences between clocks. Two nodal networks have been emphasized; however, general results using the method of conditional expectations have been arrived at. The results are to be published in the open literature in forthcoming papers. The statistical distribution of the phase difference has been reported in [18].

## Papers Published

There were two papers published which contained some early results on the unified mathematical model and mutually synchronized networks [15]. More complete results are published in two theses [19,20]. A paper was presented at ICC '81 in Denver focusing on a synchronization technique which is especially applicable in mobile user environments [11]. See also [20]. New results on the performance of a delay-compensated mutual synchronization system have been published in [18] for the two-nodal networks. Generalizations to the n-nodal case are to be published in [22] and forthcoming papers.

## Presentations

Talks on the subject of mutually synchronized networks have been given at the URSI Conference in Boulder, Colorado, January 1981 [16,21] and at the Information Theory Symposium in Santa Monica, California, February 1981 [17]. Additional talks were presented at the 1982 ICC meeting, Philadelphia, Pennsylvania [12].

## Future Directions

Future work will be directed towards extending and improving upon the progress made to date. In particular, we will make performance tradeoffs in networks which are connected in the master-slave configuration and compare this with those networks which utilize ETS/RTS mutual synchronous configurations. Emphasis will be placed upon obtaining numerical results for networks containing two or three nodes. Considerable efforts will be expended obtaining the noise theory for the stability of network time and time interval. Other critical problem areas which will continue to be addressed as time permits, include:

1. Network Stability,
2. Influence between connectivity and stability,
3. Terminal and platform dynamics,
4. Nodal processing algorithm for non-stationary networks,
5. Acquisition algorithm for the network start-up,
6. Susceptibility to interference and accuracy of time-frequency transfer,
7. Effect of link failures on performance.

We will be studying as many of these problems as progress permits. At the present time, there are no sources of funding for these continued efforts.

## 3. RETRODIRECTIVE ARRAY PROCESSING (Dr. Scholtz)

### Background

A problem of considerable current interest in antenna signal processing revolves around a concept called retrodirective array (RDA) processing. When the array is illuminated by the signal from a given source, the objective for each array element is to generate a properly-phased carrier signal so that the array will direct a beam back toward the signal source. Traditionally this has been done with a monopulse processor combined with mechanical array steering, or by phased-array processing using centrally controlled phase shifters at each array element. Retrodirective array processing provides an alternative to these approaches which require neither mechanical control of the antenna, centrally controlled phase-shifters, nor a carefully controlled array geometry.

It is worth noting that the retrodirective array concept is under consideration for use in future satellite multibeam communication systems and in Solar Power Satellite, both of which have difficult beam-pointing problems. RDA ALgorithms are also at the heart of some null-steering concepts. Calspan has developed an RDA for IFF use which is based on a simple microwave lens processing technique and operates as an Van Atta RDA. The Van Atta RDA does require strict geometric integrity of the array elements, which may not be possible in extremely large arrays.

Briefly, the RDA signal processing concept is as follows. If the source signal received at array element n is $\cos(wt+\theta_n)$ for all n, then the signal required to transmit retrodirectively must be of the form $\cos(wt-\theta_n+\theta)$ for each array element, where $\theta$ is not a function of n. The signal required to convert the received signal to the retransmitted signal via mixing at an array element is $\cos(2wt+\theta)$. The reference signal, independent of n, can be generated from one element's received signal by frequency multiplication and distributed spatially without phase shift to the remaining array elements by a returnable time system.

### Major Problems and Results

Even without considering the problems induced by modulating the signals, RDA signal processing suffers from at least two major problems.

(1) When both the received and retransmitted signals are at the same frequency, then there is the extreme isolation problem at the transceiver. During this time period, S.Y. Kang has pursued the problem of placing the retransmitted signal at some rational multiple m/n of the received signal frequency. If this shift is performed with a perfect frequency multiplier, (see Figure 3-1), then the retransmitted beam will again be in the direction of the source. Unfortunately, the m/n coherent frequency-multiplier has an n-fold phase ambiguity at its output (we assume g.c.d.(m,n)=1).

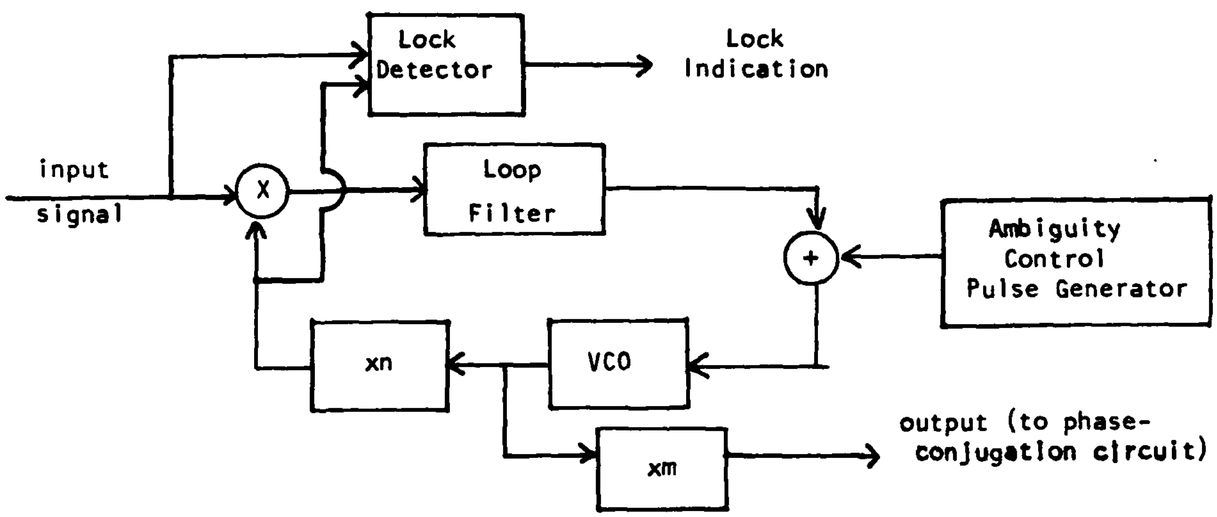



**Figure 3-1:** Coherent Frequency-Multiplier

The ambiguity can be controlled by inserting a properly designed pulse into the input of the VCO in the coherent frequency multiplier, the effect of which is to change the VCO output phase by $\frac{2\pi}{n}$ radians.

Assuming that the array is linear and the source being received is in the far field, it is possible to form a retransmit beam by "selecting" ambiguities, so that phase differences between adjacent elements coherent frequency multiplier outputs are identical. The resultant beam will point in the desired direction if the phase-ambiguity terms in adjacent outputs cancel in the phase difference calculation. to steer the beam to the proper direction, the identical phase difference value must be changed through its n-possible values in search of a maximum array received power indication.

To date, the statistics of the coherently frequency-shifted and retransmitted beam have been determined as a function of array element signal-to-noise ratio. The use of lock-detector information to forestall ambiguity-slips in various phase-locked loops and preserve beam integrity is being studied in a simple 3-element array simulation.

(2) In receiving and tracking the phase of the source signal, an array element uses the signal only from its own antenna gain. This apparent loss in signal power is a major drawback to the retrodirective concept. The question which we wish to address involves methods for overcoming this deficiency by cooperation among adjacent array elements. Specifically, the ingredient which is not generally present in some variations of pure RDA theory is nearly fixed local geometry. Information about local geometry along with signals from adjacent array elements may allow an array element to overcome the above problems. For example, in a linear uniform array illuminated by a plane wave, phase differential between received signals of adjacent elements must be a constant across the array. In the previous period, B. Eisenhart studied likelihood reception of signals by an array of known linear geometry and used this to indicate how the array element's phase-locked loops should be coupled to improve receiving signal-to-noise ratio. The results of this recoupling, when evaluated in the presence of additive white receiver noise, indicate that the signal-to-noise ratio achieved in the phase-locked loop of the central array element's receiver can be as high as the signal-to-noise ratio in the single phase-locked loop

of a perfect phased-array receiver, have been reported in [23].

Eisenhart's early work assumed perfect linear array geometry, a far-field pilot source, perfectly matched VCO's for each array element, and a fully-coupled, two-integrator controller. One method for weakening the requirement of linear array geometry involved coupling the array by only interconnecting adjacent loops. The effect on each of several schemes for accomplishing this, was to make the number of required integrators proportional to the array size. To eliminate array end effects and estimate the performance of large arrays coupled in this manner, a linearized analysis of an infinite weakly-coupled linear array was performed for a simple coupling scheme, and will be reported in the near future.

Another approach, adaptive in nature, to accomplish full coupling of a retrodirective array of unknown geometry has been developed by A. Netch. The scheme is nested, with nodes in the nesting tree (see Figure 3-2) being called array geometry-tracking loops (AGL's). At the base of the tree in the relatively high signal-to-noise ratio (SNR) portion of the system are two additional tracking loops, one for the beam-direction angle, and one for carrier-tracking. A major advantage of this system is that the AGL's, being loops to eliminate array element relative-motion effects, are presumably extremely narrowband and can operate at the relatively low SNR's present in the initial nesting levels. The rapid response loops for carrier tracking and beam-steering are in positions where the full array gain is available to improve performance.

Netch's system has been simulated, and shows nearly optimal performance (i.e., performance identical to perfectly phased array) at moderately high SNR's; an acquisition scheme has been implemented, and feasibility demonstrated. Theoretical analyses of performance have been developed for high SNR situations.

Eisenhart, Kang, and Netch are all in the process of writing their respective theses and producing manuscripts to be submitted for publication. Copies will be forwarded to AFOSR as they become available.

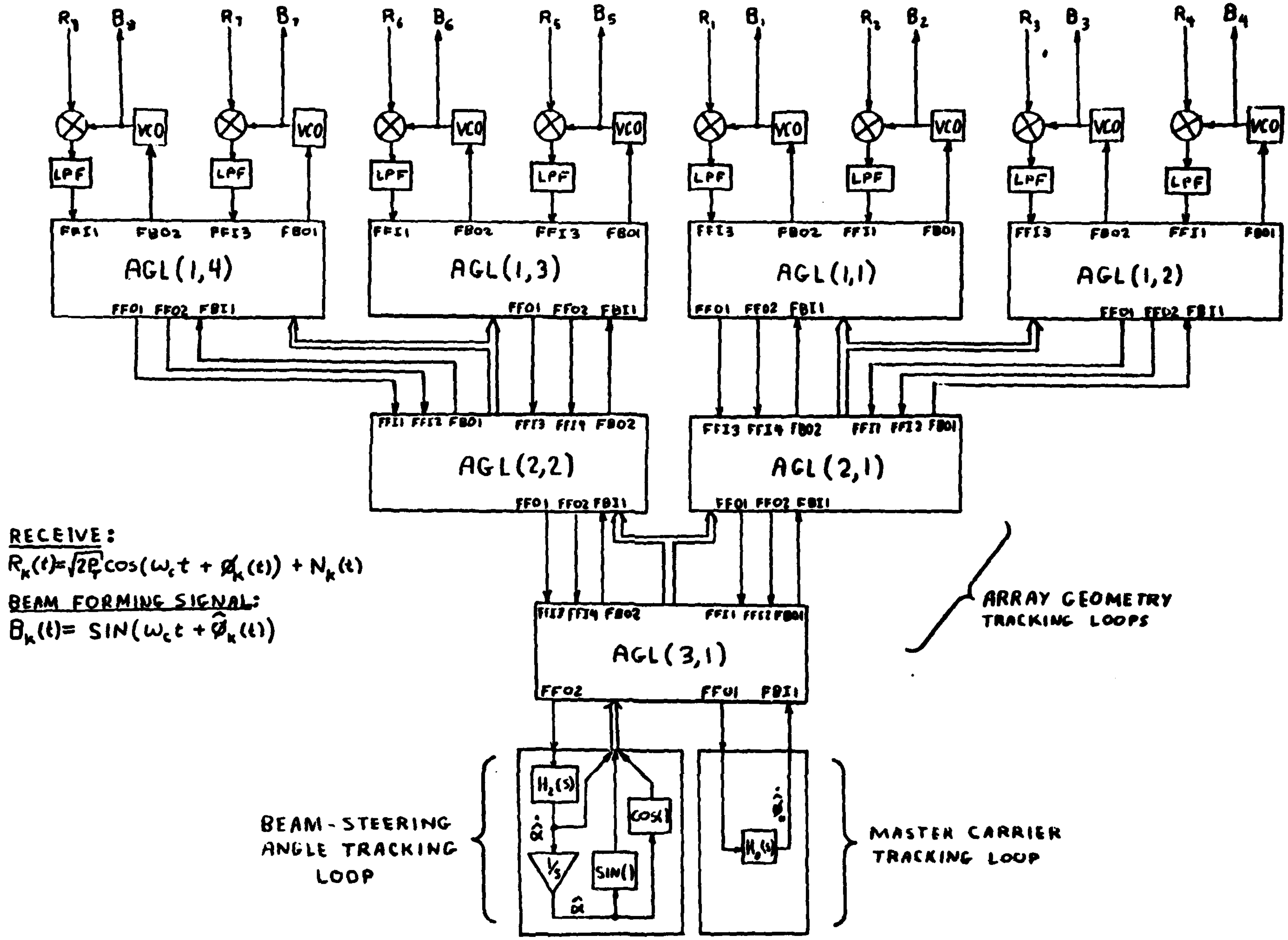
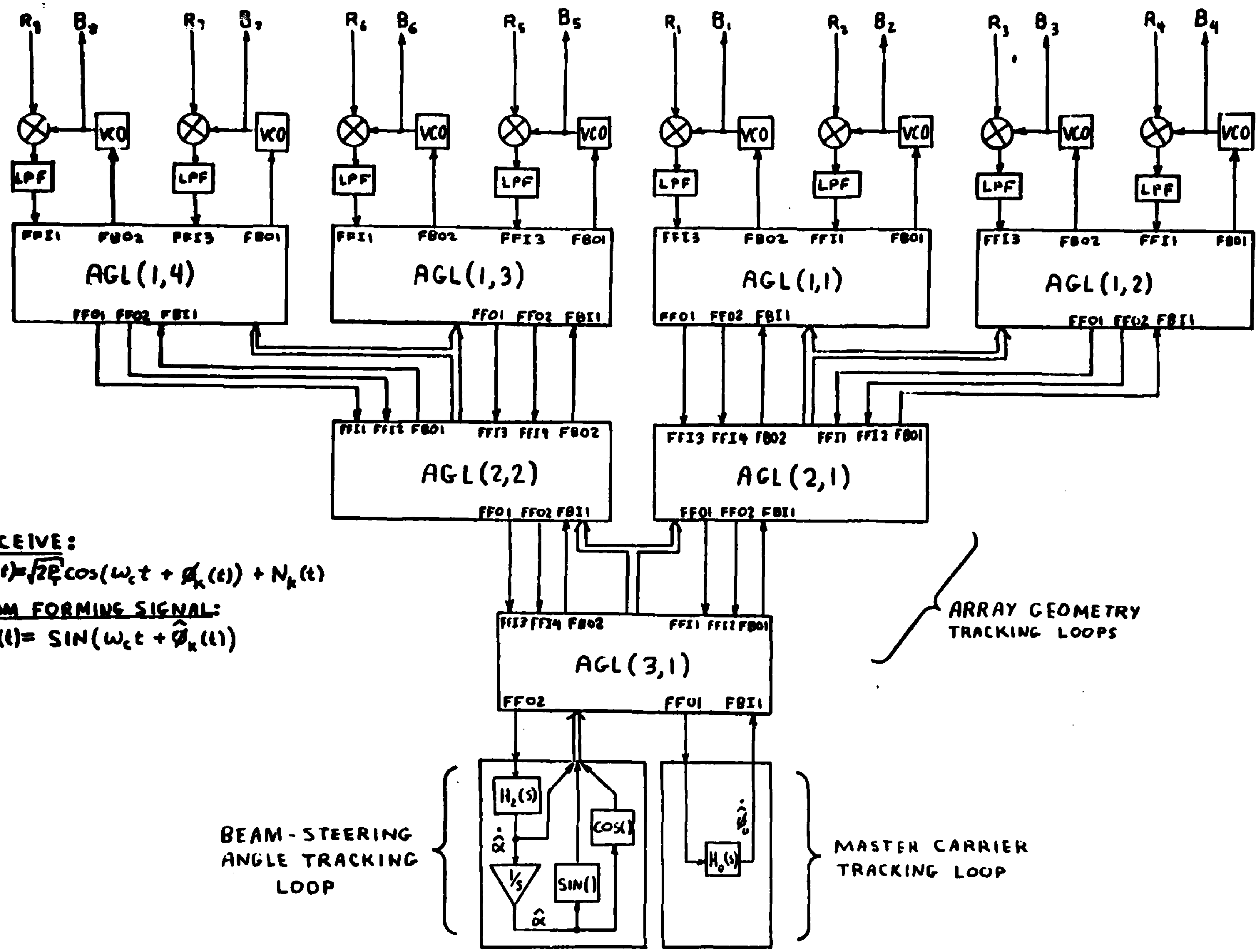



Figure 3-2: Eight Element Coupled RDA




**RECEIVE:**

$R_k(t) = \sqrt{2P}\cos(\omega_c t + \phi_k(t)) + N_k(t)$

**BEAM FORMING SIGNAL:**

$B_k(t) = \mathrm{SIN}(\omega_c t + \hat{\phi}_k(t))$

Figure 3-2: Eight Element Coupled RDA

B. List of Participating Personnel

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| William C. Lindsey | Principal Investigator |
| Robert A. Scholtz | Principal Investigator |
| George P. Papavassilopoulos | Co-Investigator |
| John A. Silvester | Co-Investigator |

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| Chit-Sang Tsang | Research Assistant |
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